The Final Measurement of ε'/ε from KTeV

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- Introduction to ε'/ε
- The KTeV Experiment
- Overview of Analysis
- Measurements of ε'/ε and other K^0 parameters
- Summary

KTeV Collaboration: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Sao Paolo, UCLA, Virginia, Wisconsin

Kaons and the CKM Matrix

• 1964 observation of $K_L \to \pi^+\pi^-$ demonstrated CP violation and presented problem for the electroweak theory with 2 generations

• Kobayashi and Maskawa recognized that 3 generation theory allowed CP violation, with a single CP-violating quantity

• For decades, however, there was only one measured CP violating parameter, ε, describing an asymmetry between $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$ mixing – "indirect" CP violation

• Search for "direct" CP violation (ε′) motivated many of the kaon experiments done during the 40 years following discovery of CPV

ε′/ε : Indirect vs. Direct CP Violation

$$K_L \sim K_{odd} + \varepsilon K_{even}$$

"Direct" in decay process

$K_{odd} \xrightarrow{\varepsilon'} \pi\pi \xleftarrow{} \varepsilon K_{even}$

"Indirect" from asymmetric $K^0 - \overline{K}^0$ mixing

$\pi\pi$

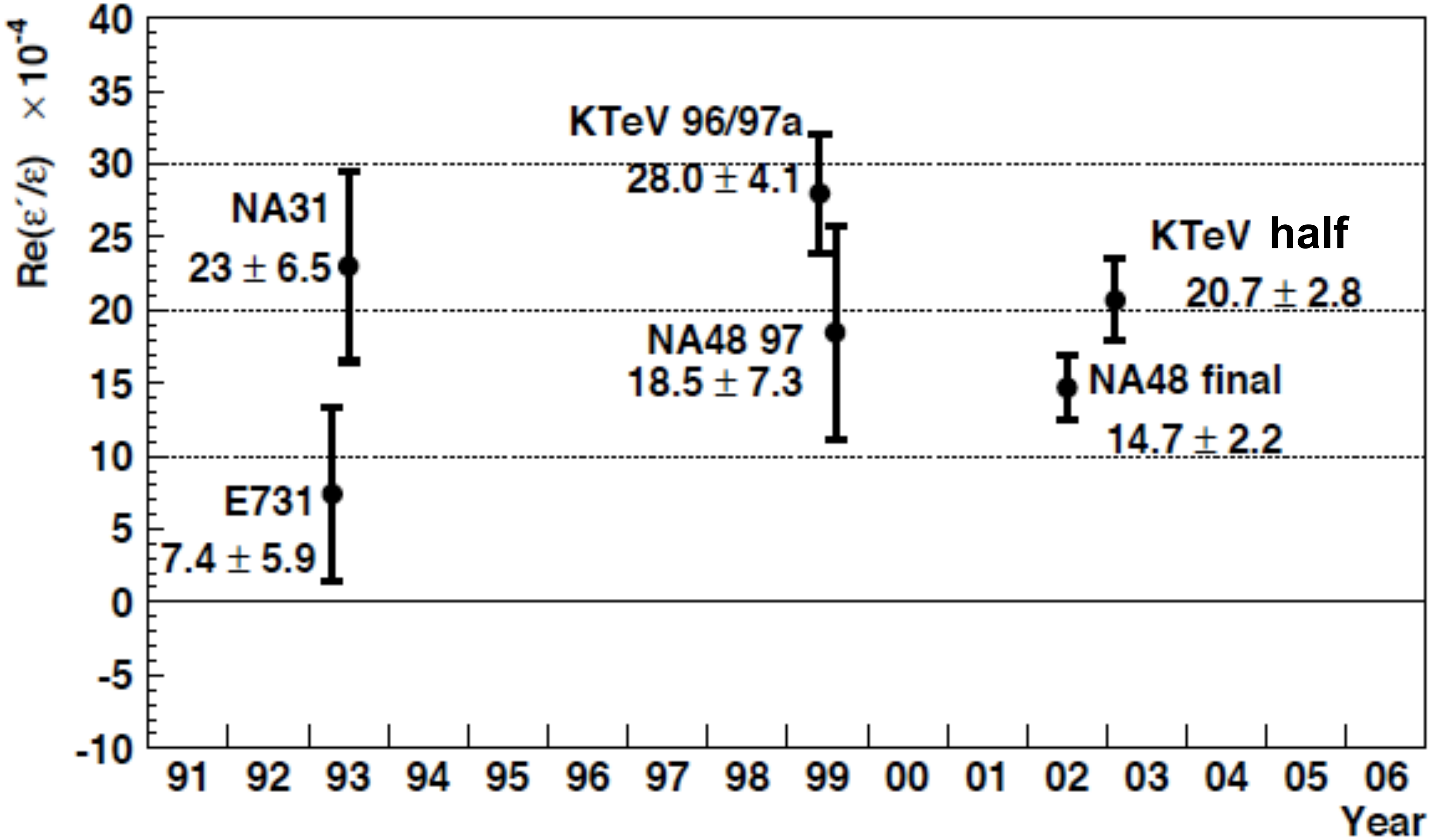
To distinguish between direct and indirect CP violation, compare $K_{L,S} \to \pi^+\pi^-$, $\pi^0\pi^0$:

$$\mathrm{Re}\left(\varepsilon'/\varepsilon\right) \approx \frac{1}{6}\left[\frac{\Gamma\left(K_L \to \pi^+\pi^-\right)/\Gamma\left(K_s \to \pi^+\pi^-\right)}{\Gamma\left(K_L \to \pi^0\pi^0\right)/\Gamma\left(K_s \to \pi^0\pi^0\right)} - 1\right]$$

$\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ ⟹ direct CP violation

$$\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\overline{K}^0 \to \pi^+\pi^-)$$

"Recent" Measurements of Re(ε′/ε)



KTeV 2003 result (based on half of KTeV data sample):

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 1.5(\mathrm{stat}) \pm 2.4(\mathrm{syst})) \times 10^{-4}$$
$$= (20.7 \pm 2.8) \times 10^{-4}$$

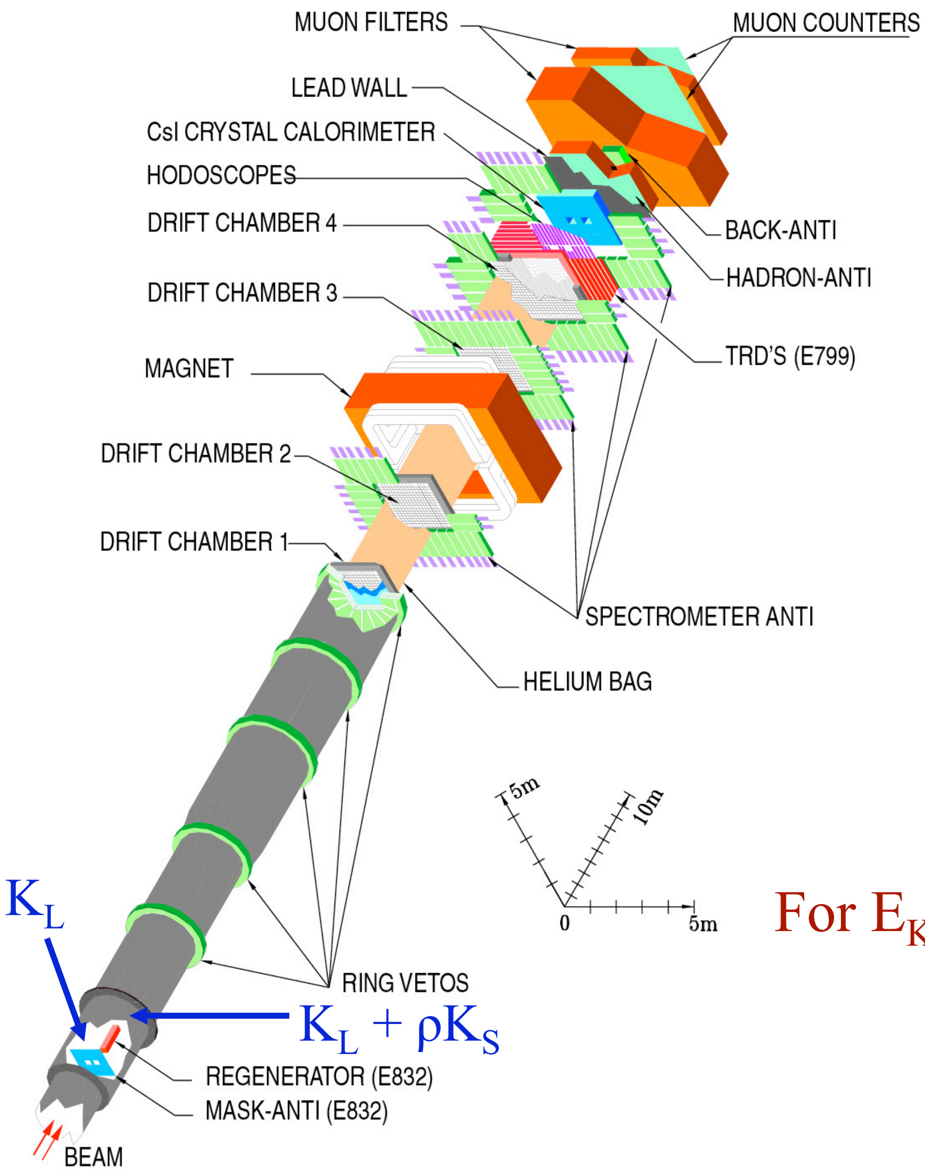
Improvement in systematics needed to take advantage of increase in statistics.

Re(ε′/ε) Systematics (2003)

	$Re(\epsilon'/\epsilon)$ Uncertainty ($\times 10^{-4}$) from:	
Source of uncertainty	$K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.58	0.18
CsI energy, position recon	–	1.47
Track reconstruction	0.32	–
Selection efficiency	0.47	0.37
Apertures	0.30	0.48
Background	0.20	1.07
z-dependence of acceptance	0.79	0.39
MC statistics	0.41	0.40
Fitting	0.30	
TOTAL	2.39	

2008 analysis of full data sample includes many improvements in charged and neutral event reconstruction and simulation.

The KTeV Detector

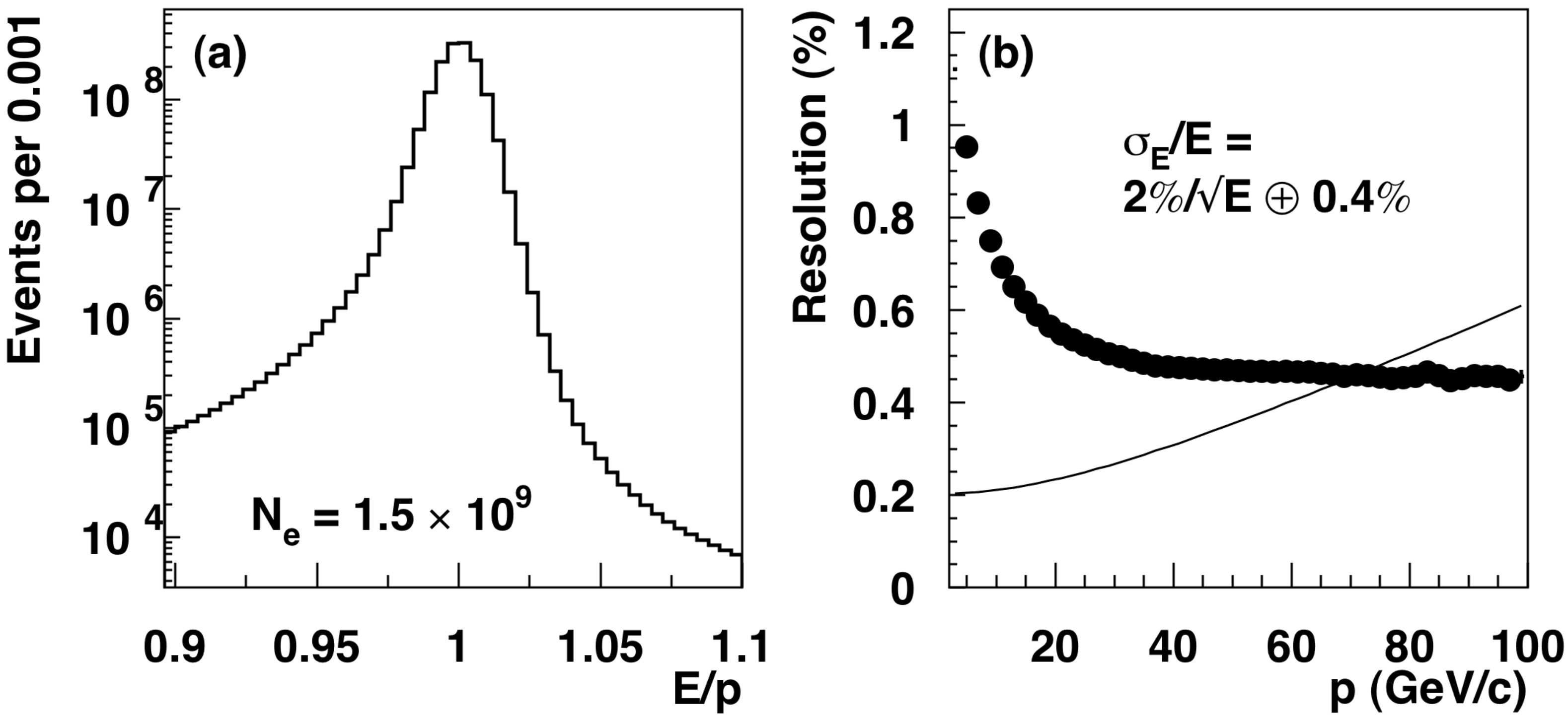


- Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from $K \to \pi^+\pi^-$
- CsI energy resolution < 1% for E_γ > 3 GeV; energy scale known to 0.05% from $K \to \pi e \nu$.

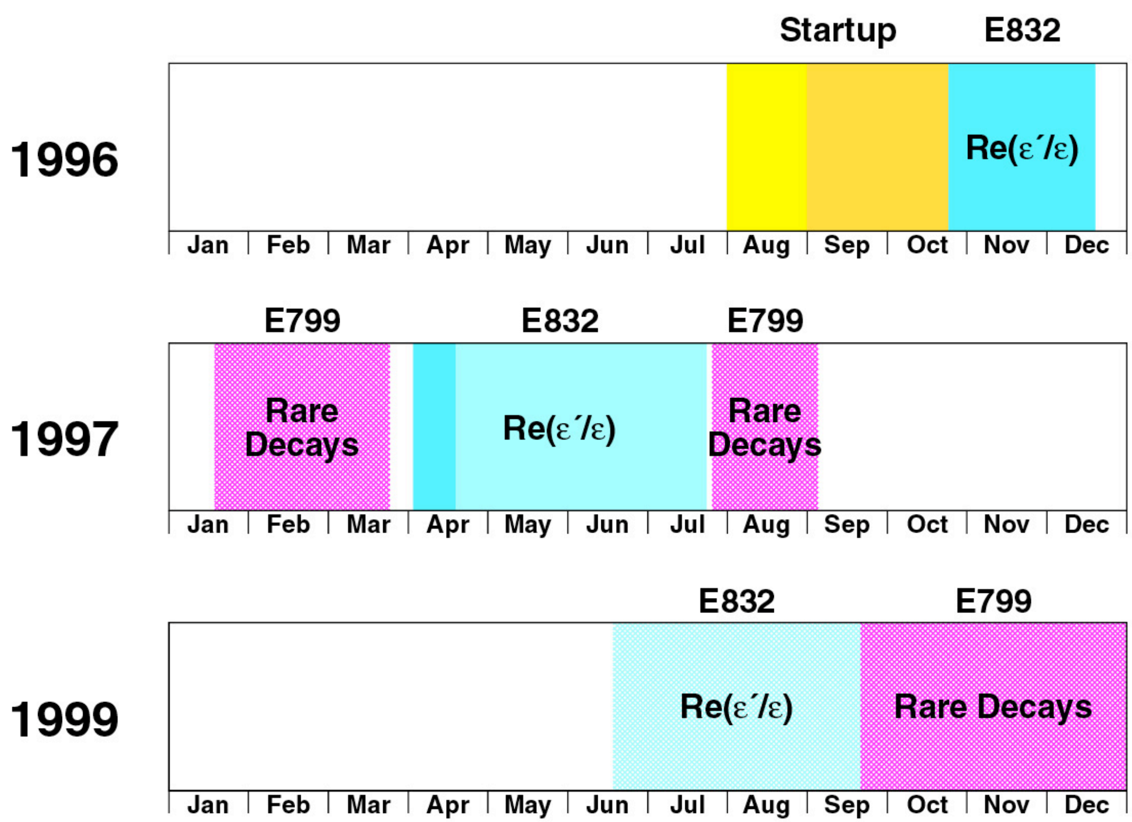
For $E_K \sim 70$ GeV, K_S: $\gamma\beta c\tau \sim 3.5$m
K_L: $\gamma\beta c\tau \sim 2.2$ km

CsI Calorimeter Performance

Full calibration sample includes 1.5 billion electrons from K→πeν.

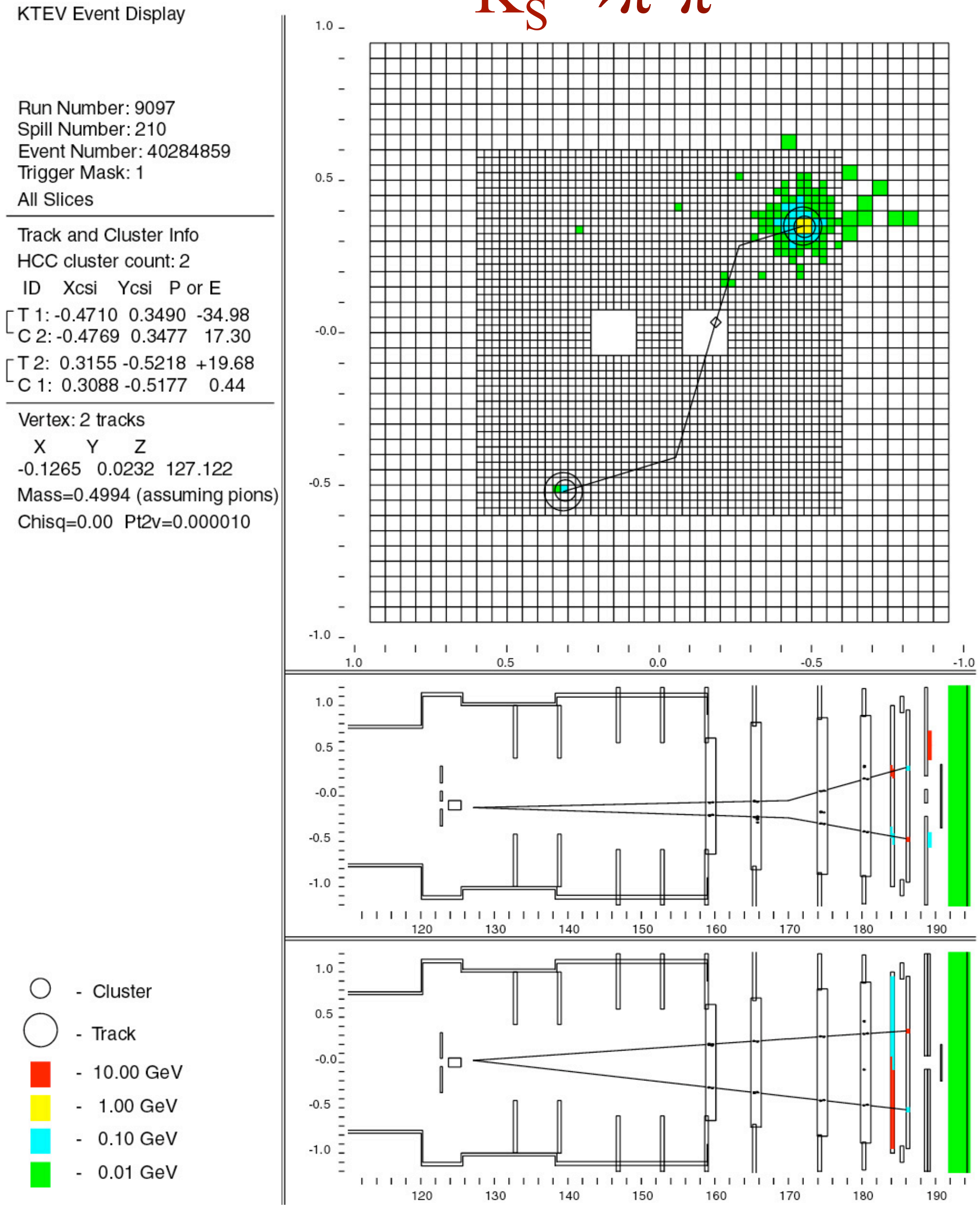


KTeV Data Samples

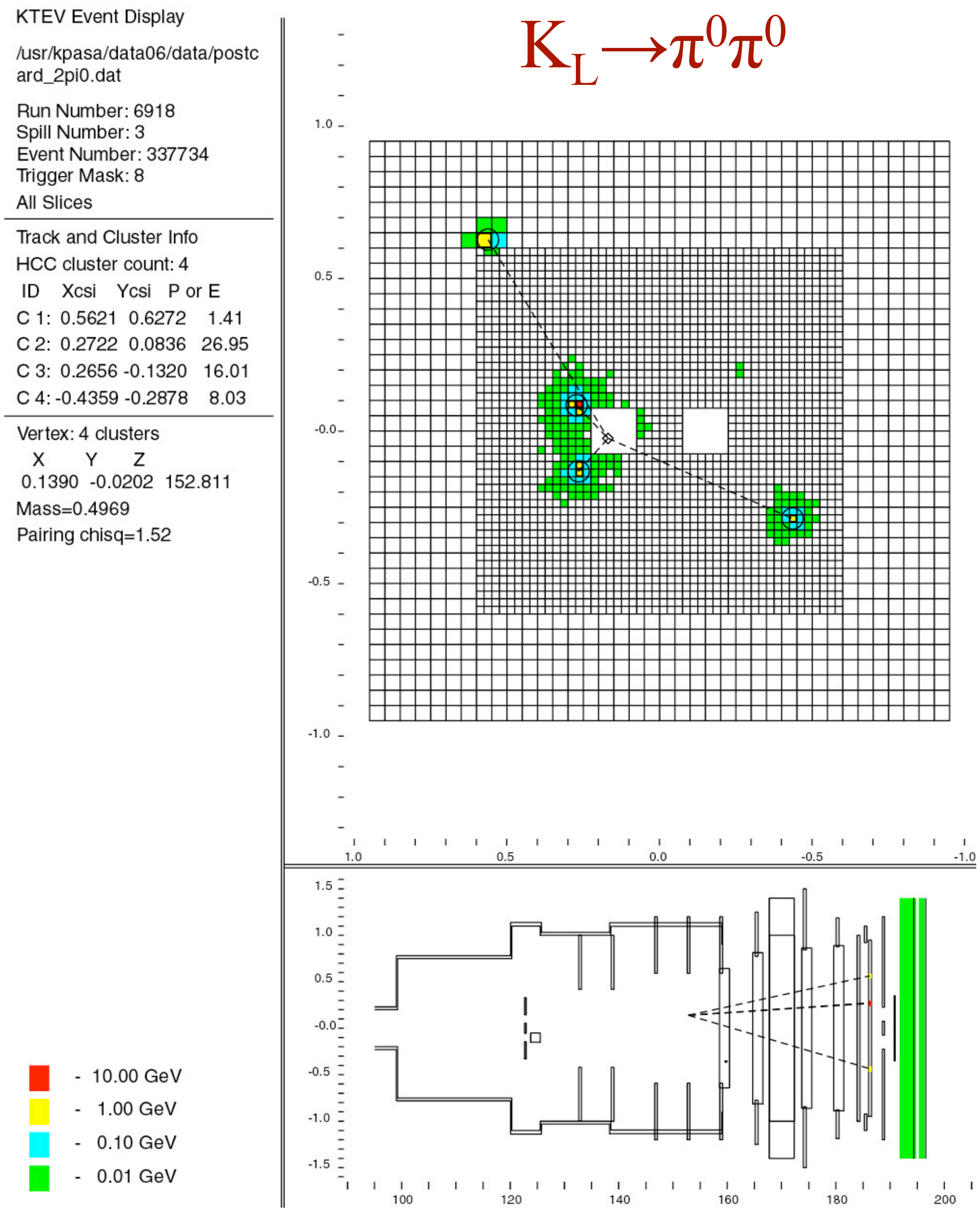


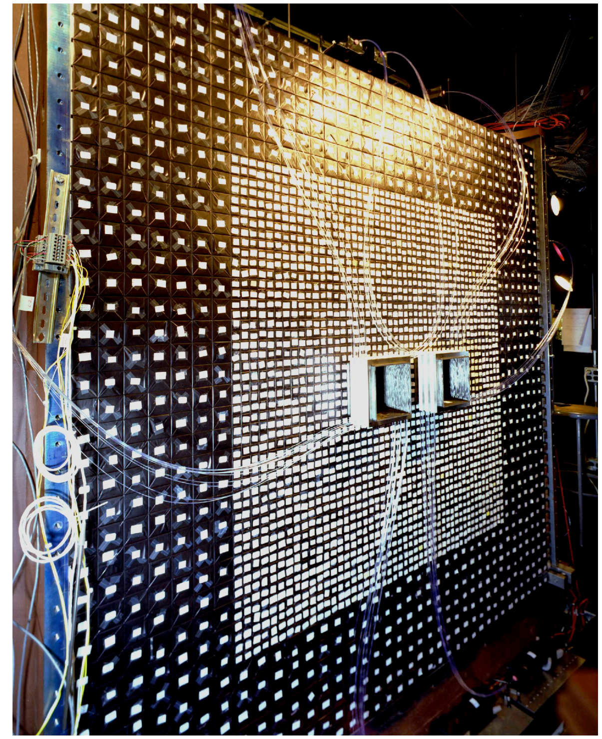
- 2003 result included ~3 million $K_L \to \pi^0\pi^0$ decays from 1996 and 1997
  - $\sigma_{stat} = 1.5 \times 10^{-4}$
- 1999 dataset contains ~3 million $K_L \to \pi^0\pi^0$ decays
  - $\sigma_{stat} = 1.5 \times 10^{-4}$
- Today: results from full data sample: $\sigma_{stat} = 1.1 \times 10^{-4}$

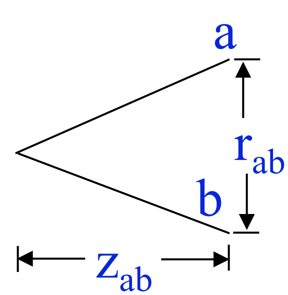
$K_S \to \pi^+\pi^-$


KTEV Event Display
Run Number: 9097
Spill Number: 210
Event Number: 40284859
Trigger Mask: 1
All Slices
Track and Cluster Info
HCC cluster count: 2
ID Xcsi Ycsi P or E
T 1: -0.4710 0.3490 -34.98
C 2: -0.4769 0.3477 17.30
T 2: 0.3155 -0.5218 +19.68
C 1: 0.3088 -0.5177 0.44
Vertex: 2 tracks
X Y Z
-0.1265 0.0232 127.122
Mass=0.4994 (assuming pions)
Chisq=0.00 Pt2v=0.000010
- Cluster
- Track
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV
1.0
0.5
-0.0
-0.5
-1.0
120
130
140
150
160
170
180
190

$K_L \rightarrow \pi^0 \pi^0$

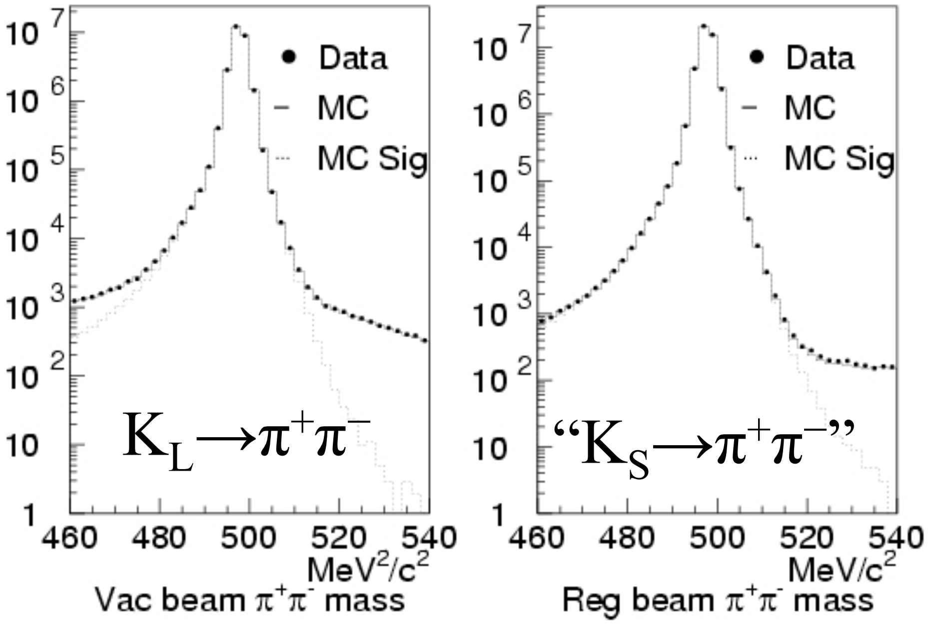




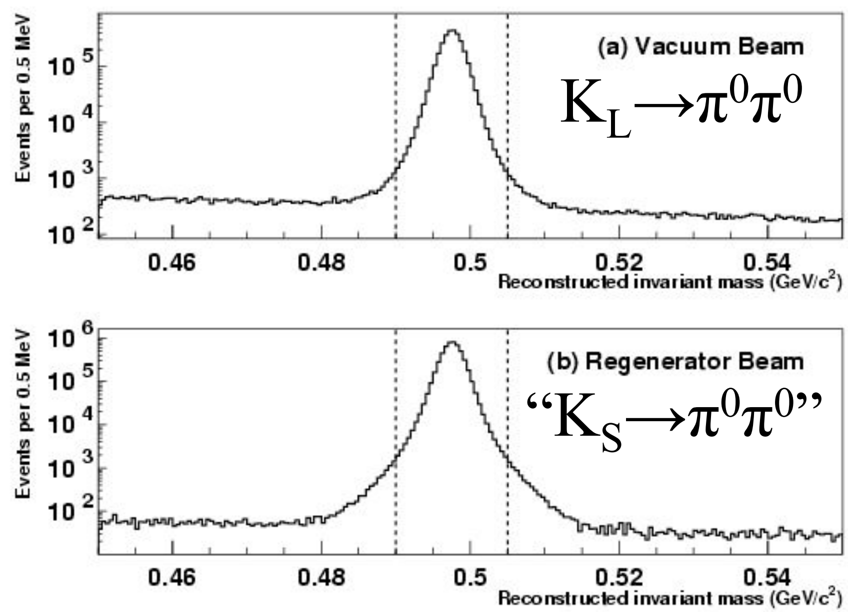


$$z_{ab}^2 \approx \frac{E_a E_b r_{ab}^2}{m_{\pi^0}^2}$$

Invariant Mass Plots



Mass resolution is ~1.5 MeV/c^2 for both decay modes.



Backgrounds and event yields

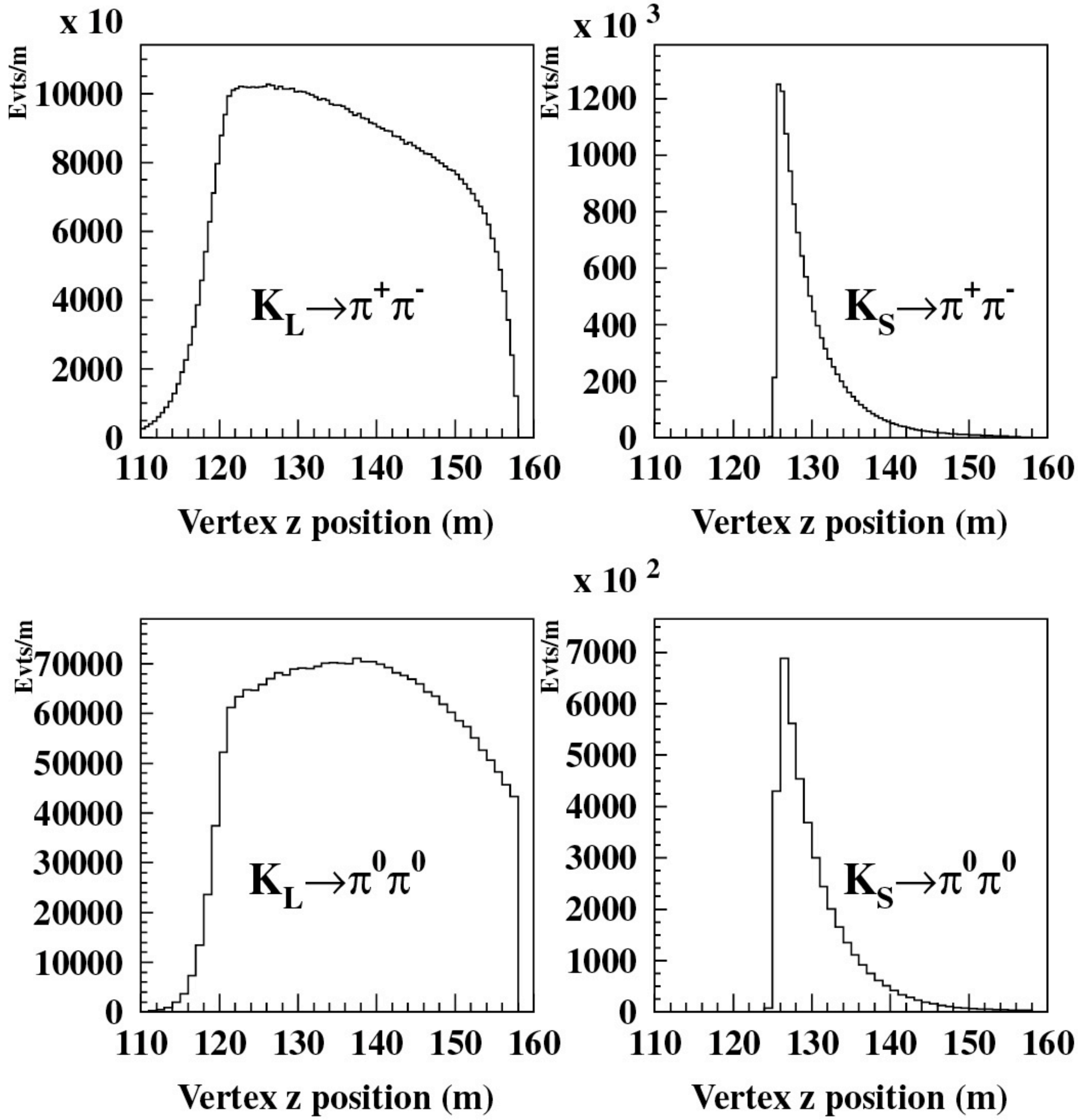
Main classes of background:

- Misidentified kaon decays
  - For $K \rightarrow \pi^+\pi^-$: $K_L \rightarrow \pi e \nu$, $K_L \rightarrow \pi \mu \nu$
  - For $K \rightarrow \pi^0\pi^0$: $K_L \rightarrow \pi^0\pi^0\pi^0$
- Scattered $K \rightarrow \pi\pi$ events
  - From regenerator and final collimator
- Backgrounds are simulated with MC, normalized to data sidebands, and subtracted
- Background level is ~0.1% for charged mode and ~1% for neutral mode.

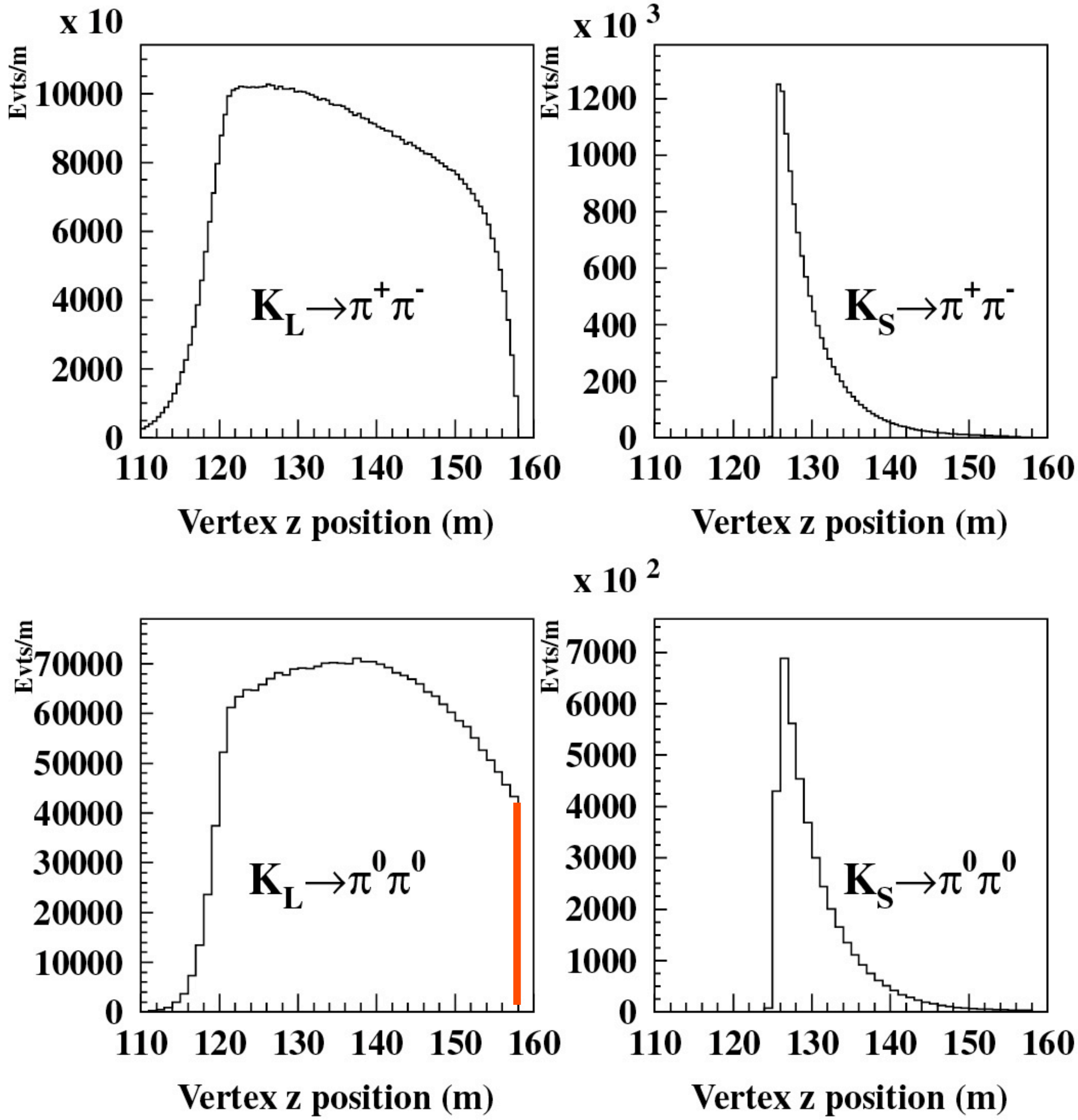
After background subtraction:

	K_L Vacuum Beam	"K_S" Reg. Beam
$K \rightarrow \pi^+\pi^-$	25,107,242	43,674,208
$K \rightarrow \pi^0\pi^0$	5,968,198	10,180,175

Reconstructed Vertex z Distributions



Reconstructed Vertex z Distributions



0.1% shift in E scale: ~3 cm shift in vertex; $\sim 1\times10^{-4}$ shift in ε'/ε

Acceptance Correction

- A detailed Monte Carlo simulation based on measured detector geometry and response is used to calculate acceptance as a function of p,z, and beam (reg or vac).
- Includes effects of accidental activity.

Many improvements compared to 2003 analysis:

More complete treatment of particle interactions with matter:

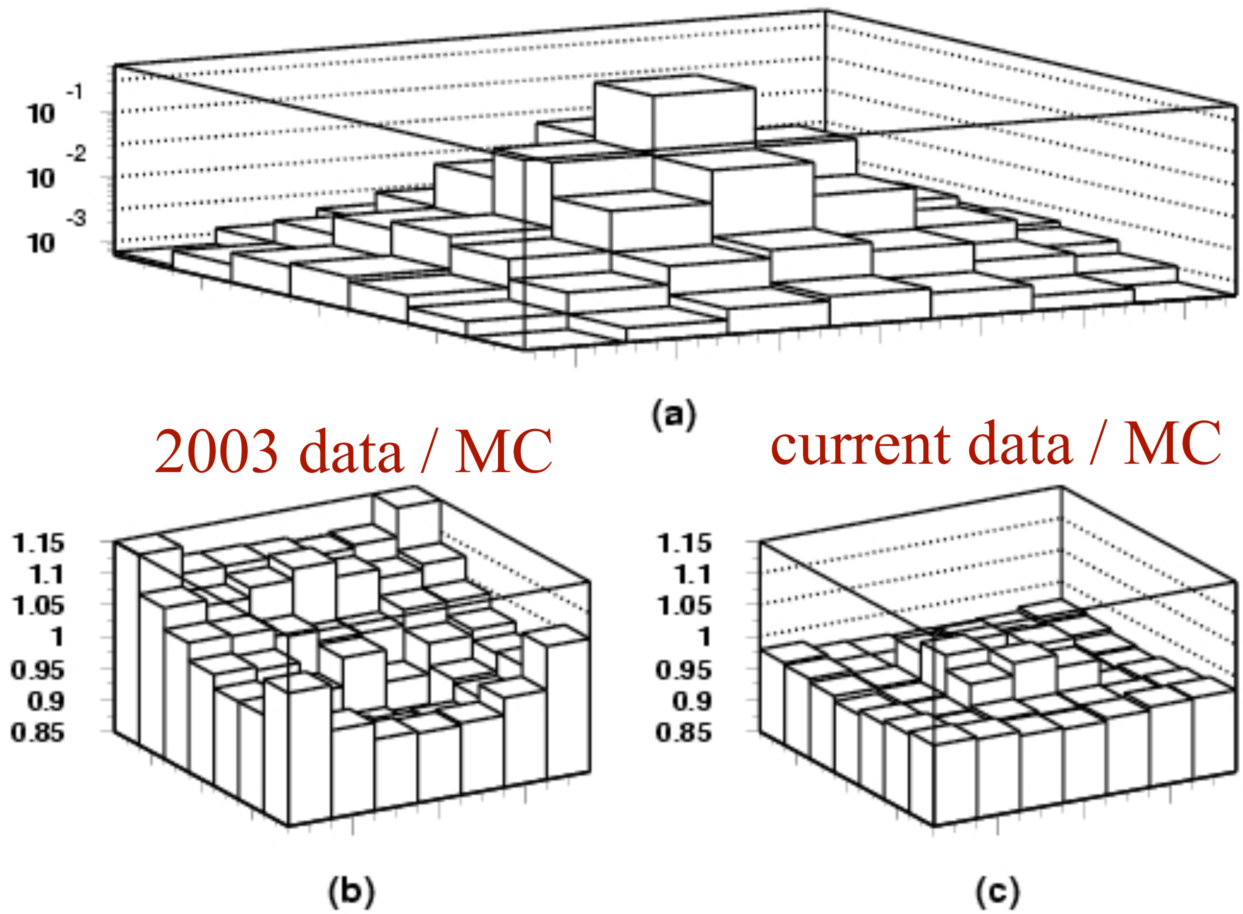
- Ionization energy loss
- Improved Bremsstrahlung
- Improved delta rays
- Hadronic interactions in drift chambers

Improved electromagnetic shower simulation:

- Shower library binned in incident particle angle
- Simulate effects of dead material (wrapping and shims) in CsI calorimeter

Monte Carlo Improvements: Simulation of photon angles

Fraction of energy in 49 crystals for electron shower

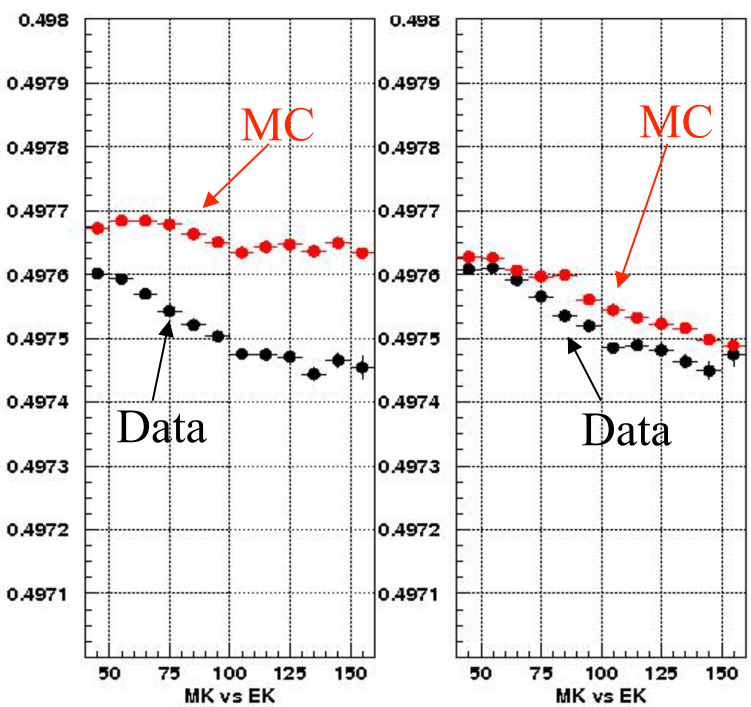


20-30 mrad incident angles used

Improved Modeling of Energy Nonlinearities

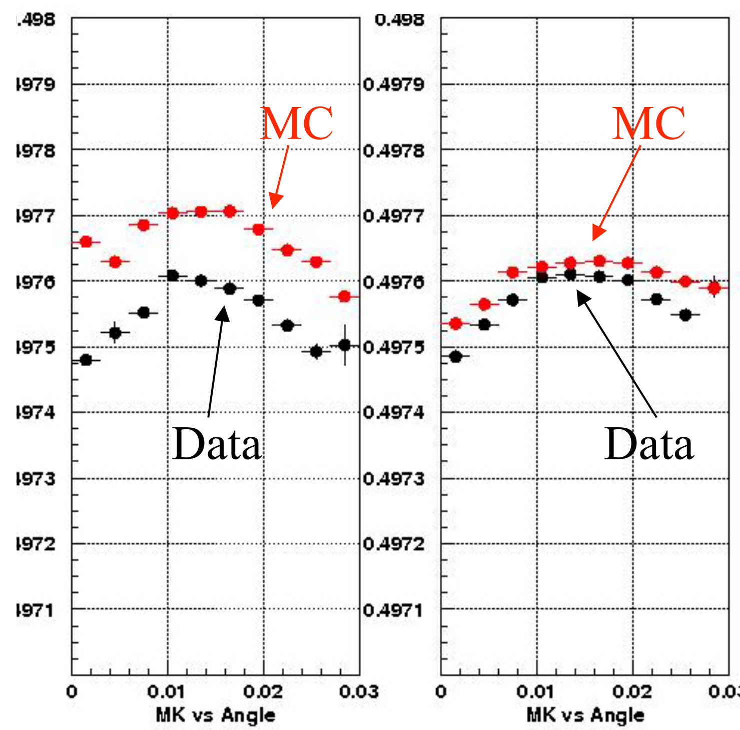
Mass vs. Energy

2003 Current



Mass vs. Photon Angle

2003 Current



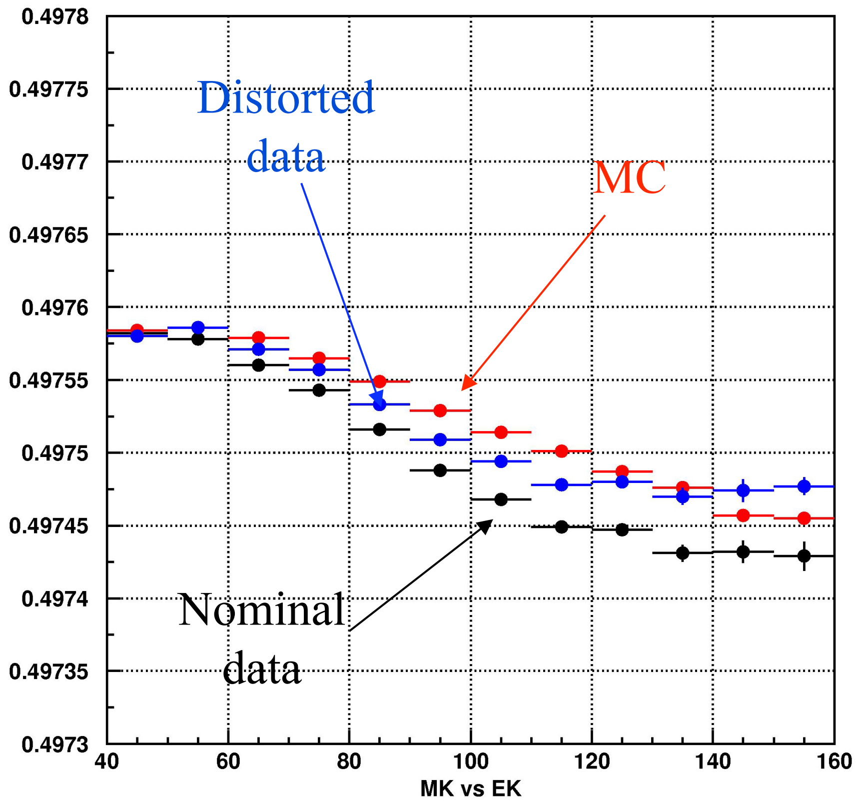
Systematic Uncertainties in Re(ε′/ ε)

Source	Error on $Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$	
	$K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI cluster reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Backgrounds	0.20	1.07
MC statistics	0.20	0.25
Total	0.81	1.55
Fitting	0.31	
Total	1.78	

Reduced from 1.47

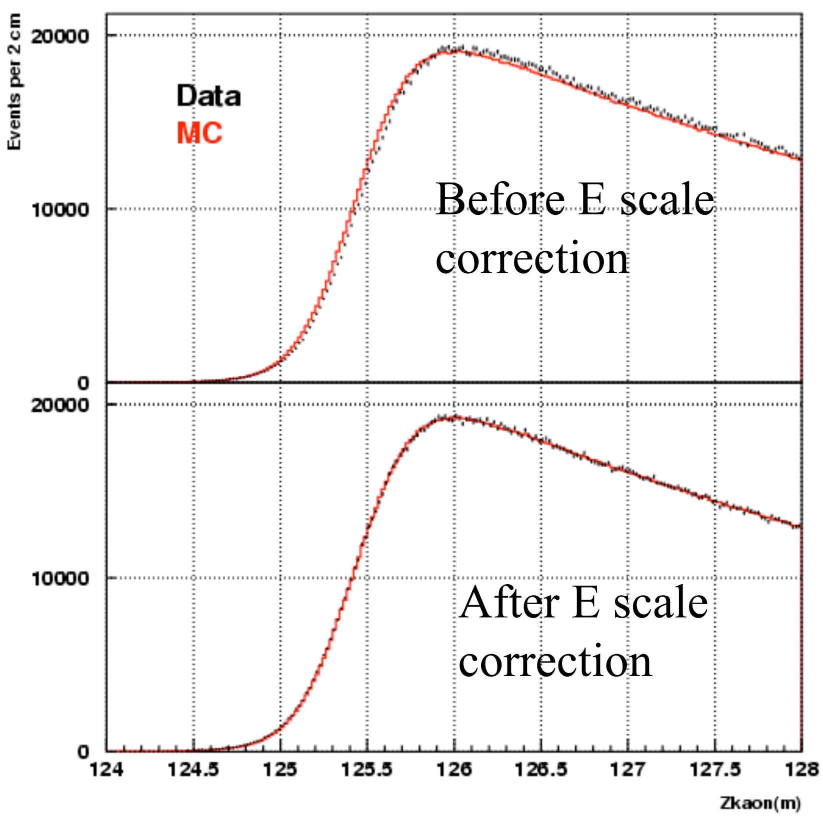
Uncertainty from Energy Non-linearity

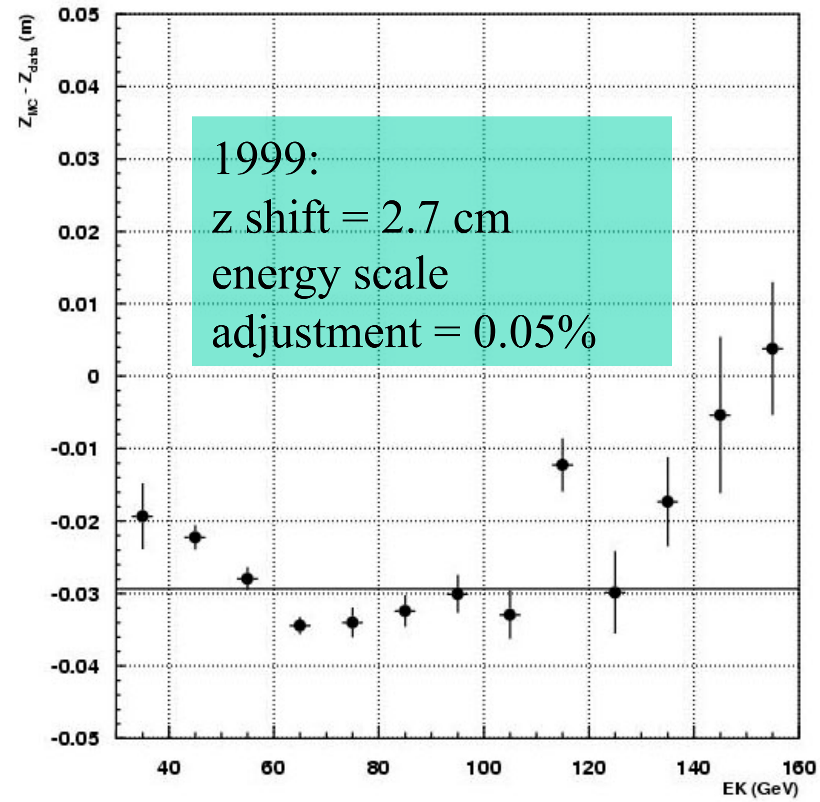
- Use M_K vs E_K plot to determine distortion that provides best data-MC match
- 0.1%/100 GeV nonlinearity applied to data for 1997 and 1999
- 0.3%/100 GeV nonlinearity for 1996
- Change in Re(e′/e)
  - 1996: -0.1×10^{-4}
  - 1997: -0.1×10^{-4}
  - 1999: $+0.2 \times 10^{-4}$
- Systematic error: $\pm 0.15 \times 10^{-4}$



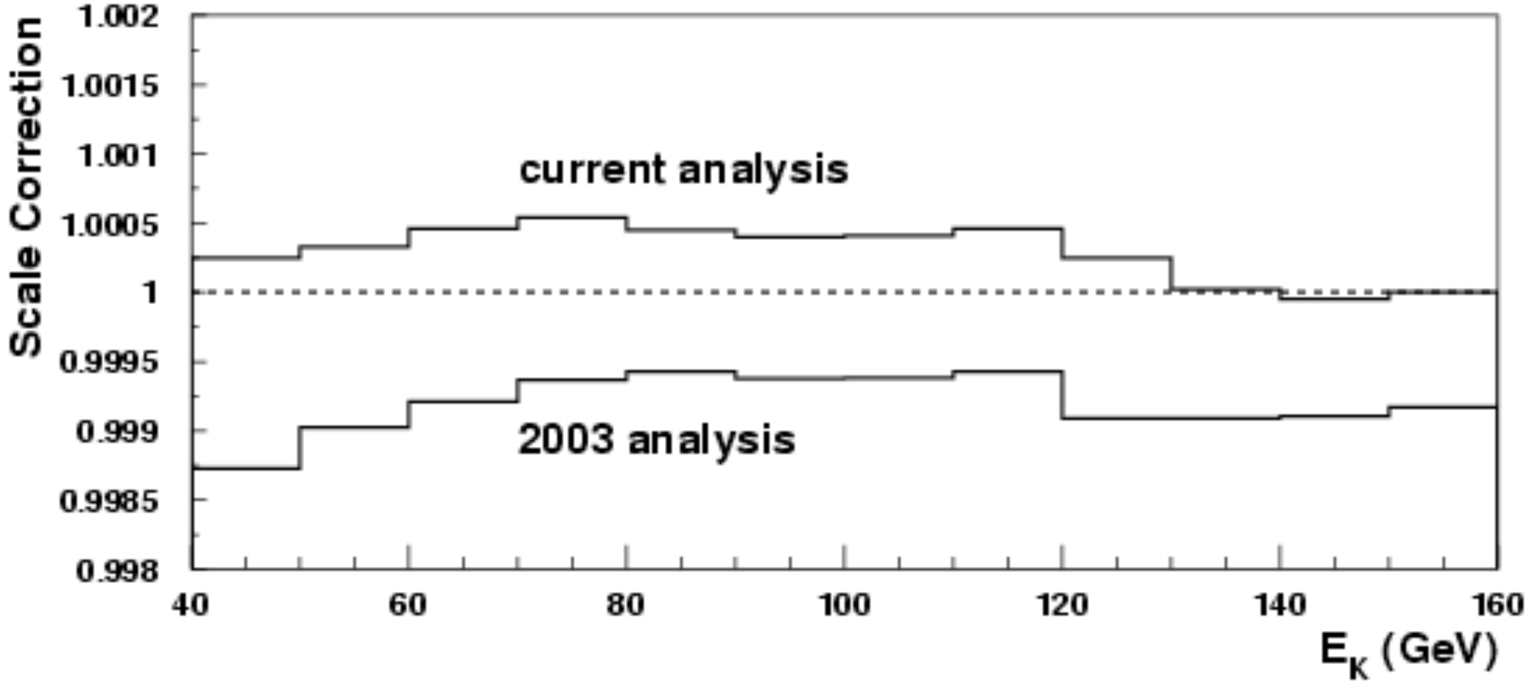
Calorimeter Energy Scale

- Calorimeter calibrated with momentum-analyzed electrons from $K \rightarrow \pi e \nu$
- Final energy scale adjustment based on $K^0 \rightarrow \pi^0 \pi^0$ at regenerator edge

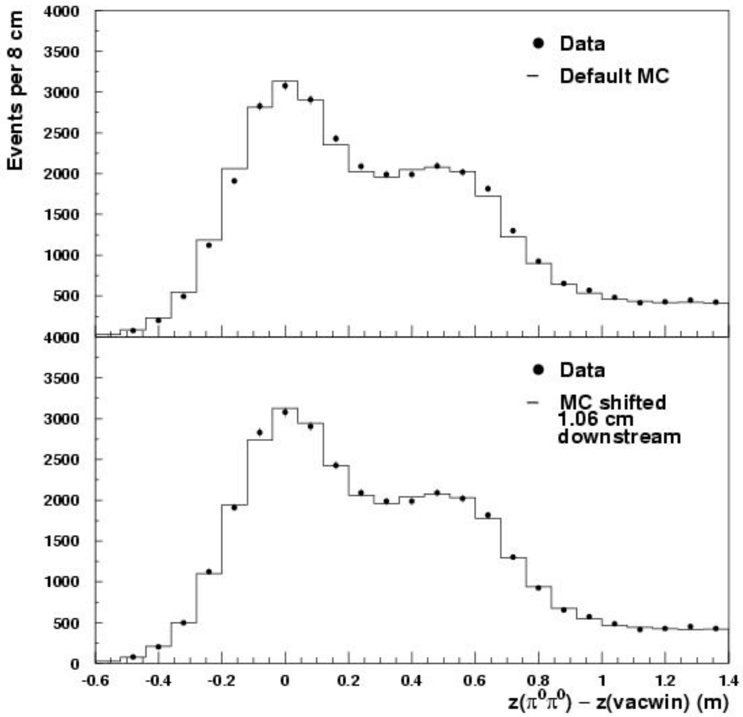




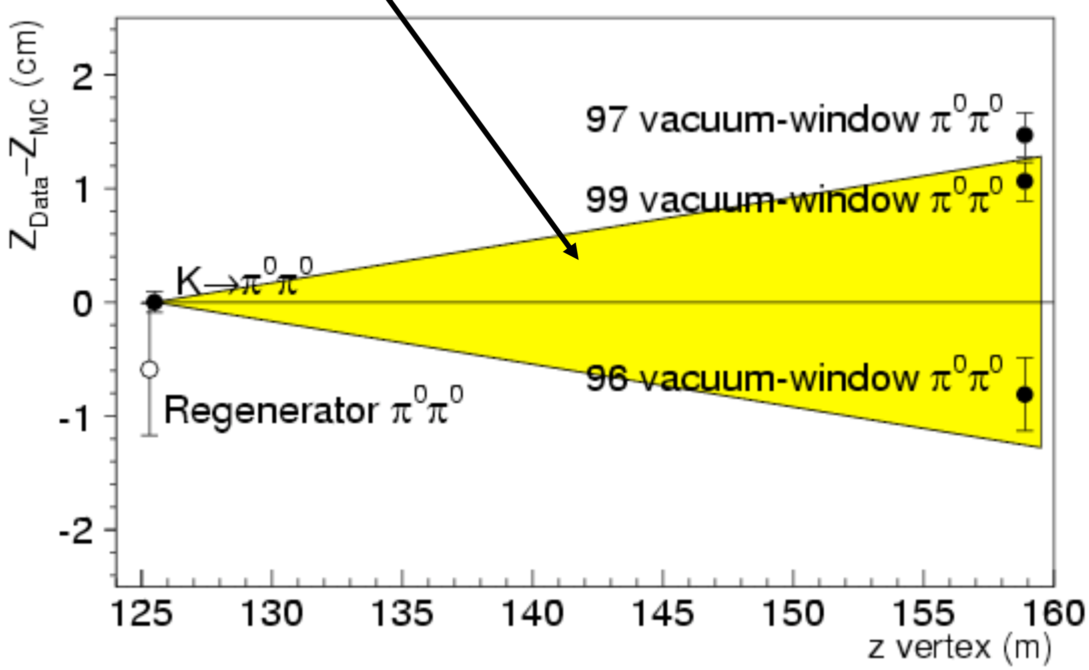
Improvement in Energy Scale Correction



Energy scale fixed at regenerator edge → check scale at vacuum window.



Uncertainty in Re(ε′/ε): $\pm 0.65 \times 10^{-4}$



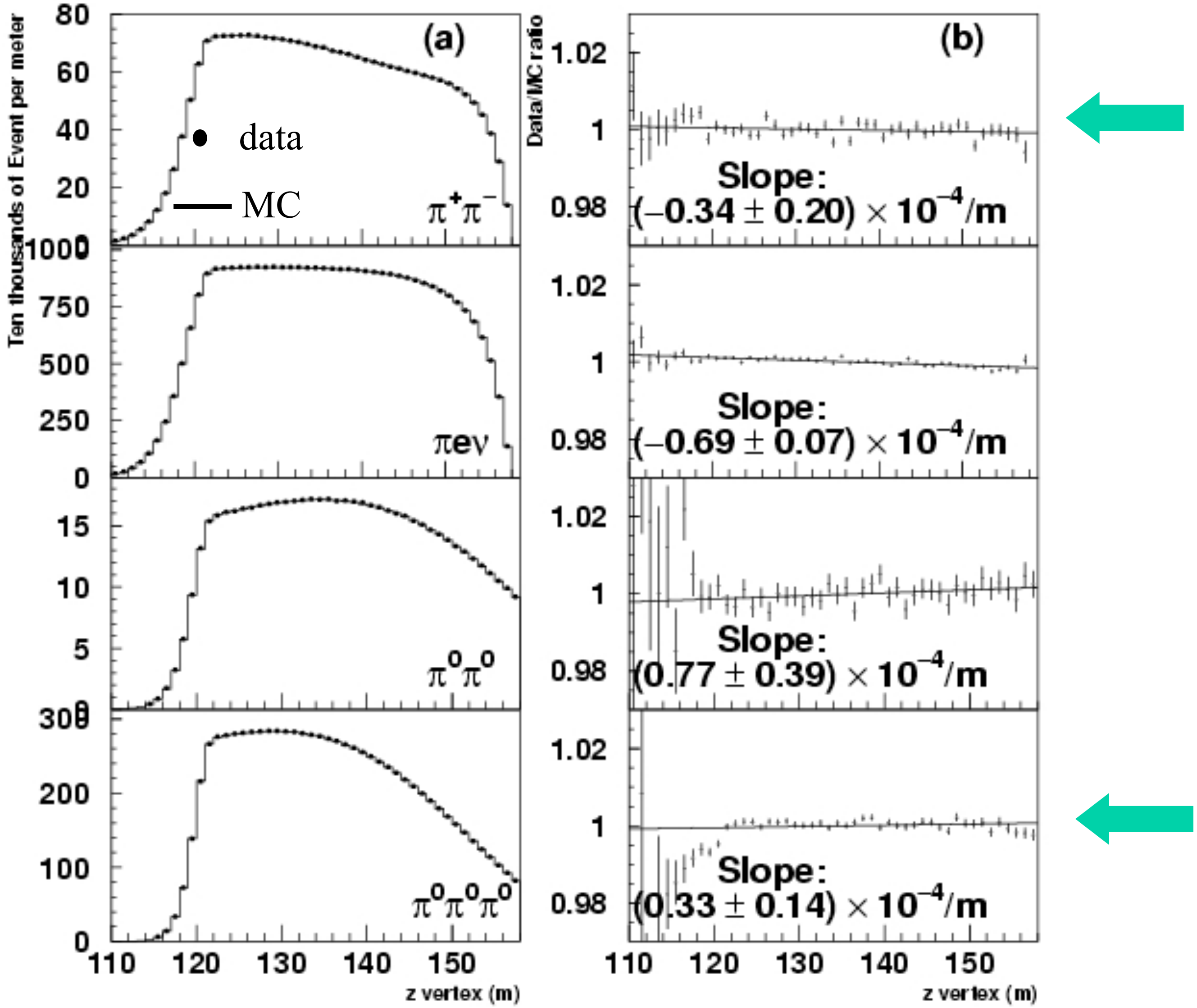
~×2 improvement compared to previous analysis.

Data – MC comparisons of z vertex distributions

Difference between mean z vertex in reg and vac beams is about 6 m

$\Rightarrow$

$\delta \mathrm{Re}(\varepsilon'/\varepsilon)$
$\approx$ data/mc slope



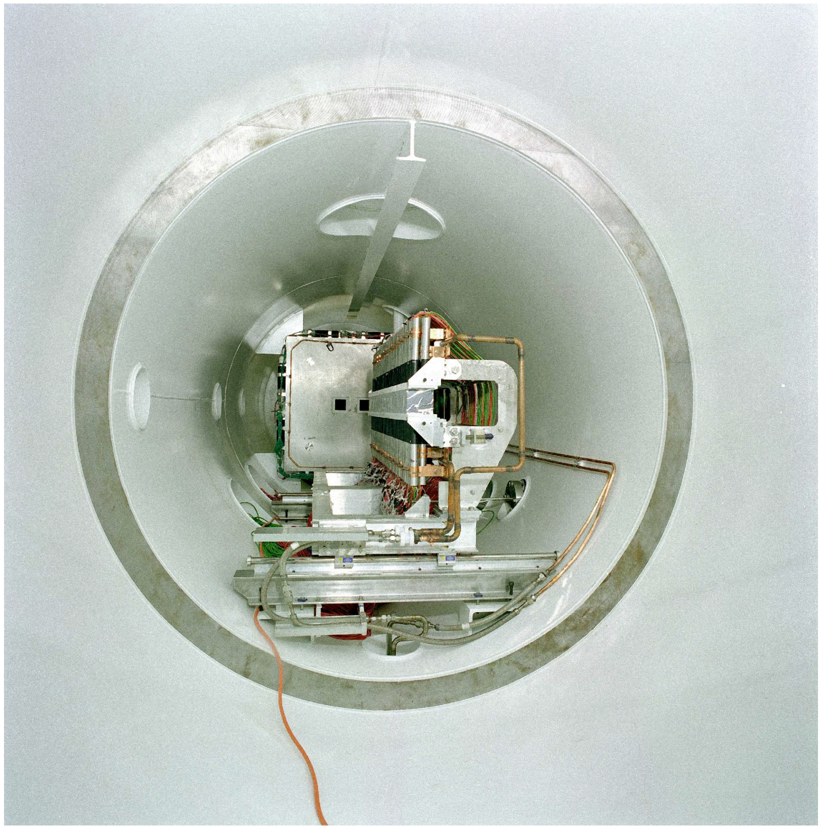
Calculating Re(ε′/ε)

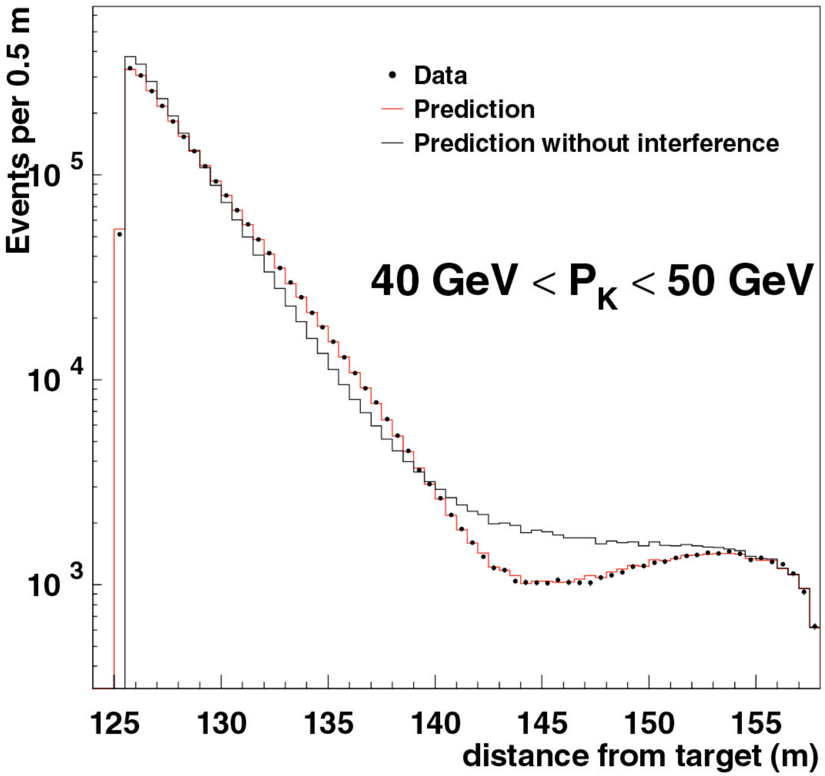
Naively,

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\dfrac{\mathrm{N(Vac}\ \pi^+\pi^-)}{\mathrm{Acc(Vac}\ \pi^+\pi^-)} \Big/ \dfrac{\mathrm{N(Reg}\ \pi^+\pi^-)}{\mathrm{Acc(Reg}\ \pi^+\pi^-)}}{\dfrac{\mathrm{N(Vac}\ \pi^0\pi^0)}{\mathrm{Acc(Vac}\ \pi^0\pi^0)} \Big/ \dfrac{\mathrm{N(Reg}\ \pi^0\pi^0)}{\mathrm{Acc(Reg}\ \pi^0\pi^0)}} - 1\right],$$

but regenerator beam is not purely K_S.

K_L - K_S Interference Downstream of Regenerator



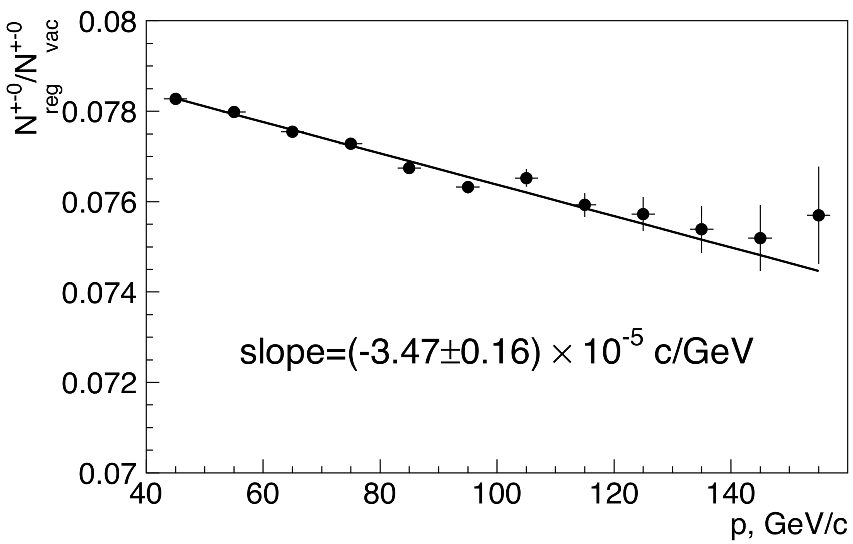


Regenerator Vertex Z distribution

$$N(p,z) \propto |\eta|^2 e^{-\Gamma_L t} + |\rho|^2 e^{-\Gamma_S t} + 2|\eta||\rho| e^{-(\Gamma_S+\Gamma_L)t/2} \cos(\Delta m t + \Phi_\rho - \Phi_\eta)$$

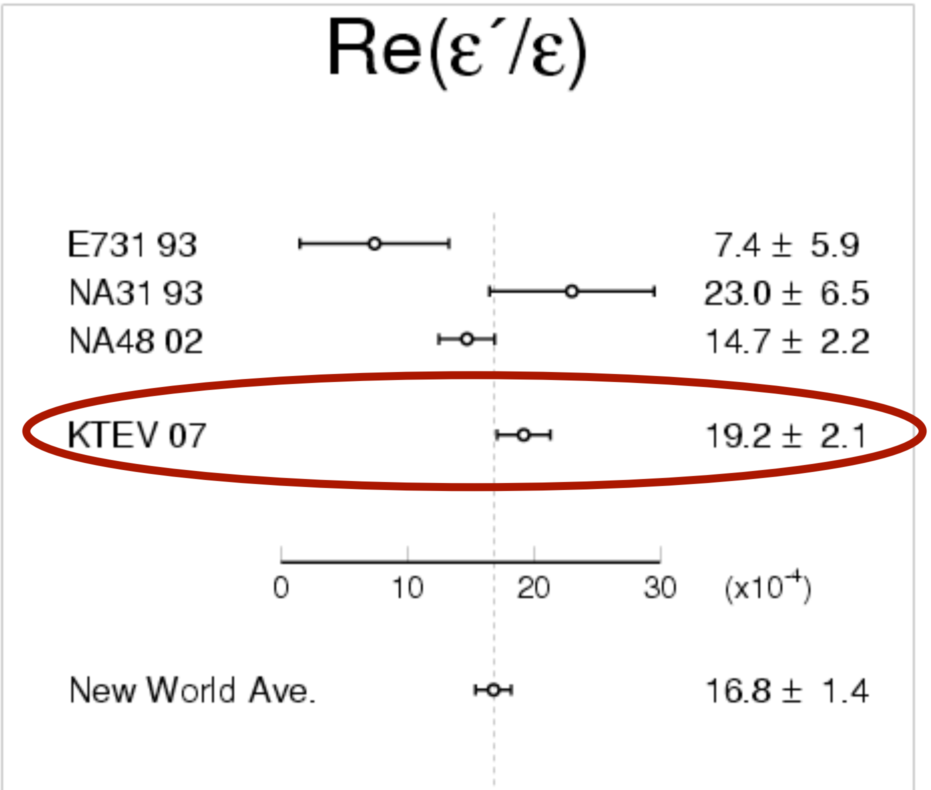
Fit to Extract Re(ε′/ε)

- Acceptance applied to prediction function in 2 m z bins and 10 GeV/c momentum bins
- Data are fit in 10 GeV/c momentum bins and a single z bin for each beam
- K_L fluxes are floated in 10 GeV/c p bins separately for charged and neutral mode
- Regenerator beam attenuation measured directly from data using $K_L \rightarrow \pi^+\pi^-\pi^0$ decays (special trigger in 99 gave 9-fold increase in sample):



KTeV Result: $\mathrm{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})] \times 10^{-4}$

$$= (19.2 \pm 2.1) \times 10^{-4}$$



World average:

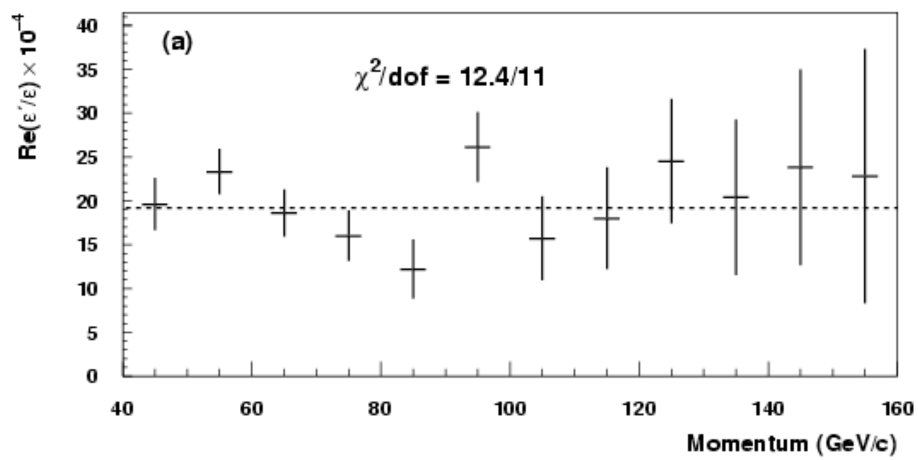
$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$

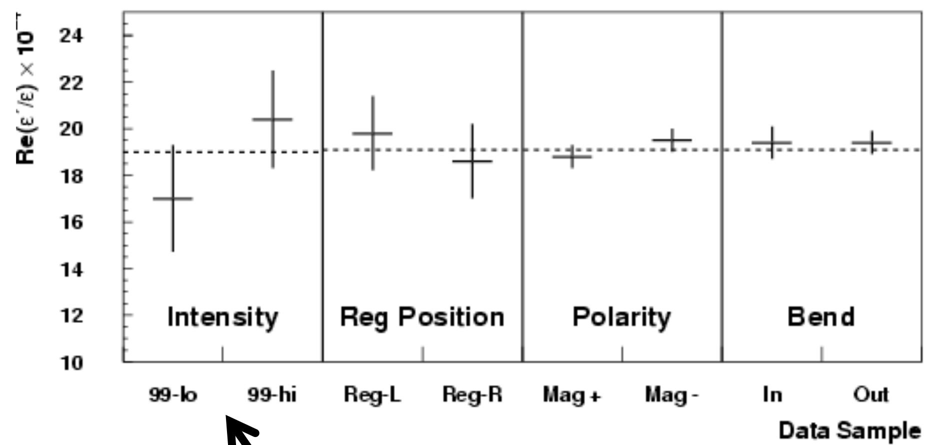
(confidence level = 13%)

(KTeV 2003: $\mathrm{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\mathrm{stat}) \pm 2.4\ (\mathrm{syst})] \times 10^{-4}$)

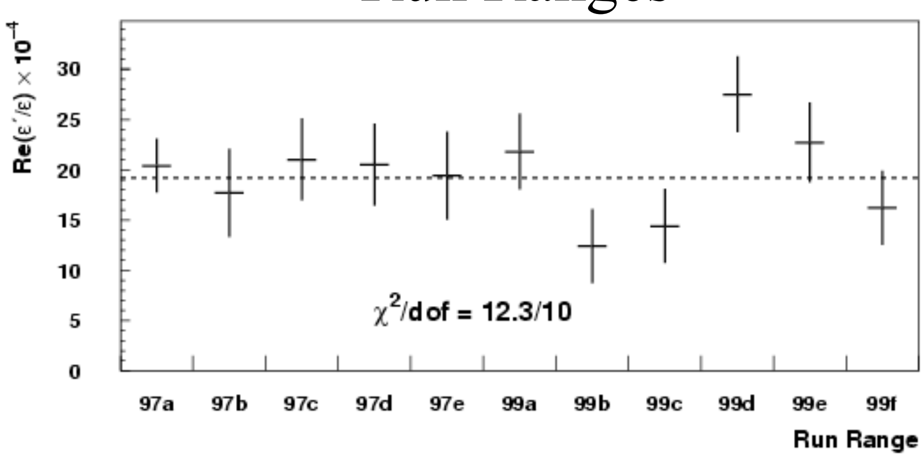
Re(ε′/ε) Cross checks

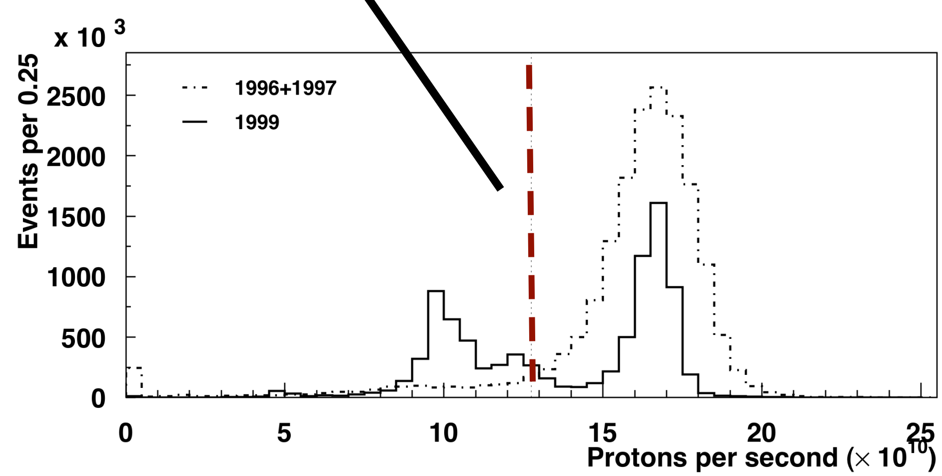
Momentum Bins





Run Ranges





Fit Strategy for z-binned Fits

- In contrast with Re(ε′/ε) fit, in which a single ~50 m z bin is considered, we now fit the regenerator beam data in 2 m z bins.
- Float $\Delta m = m_L - m_S$, τ_S, ϕ_ε, Re(ε′/ε), Im(ε′/ε) with no CPT assumption.
- CPT constraint ($\phi_\varepsilon = \phi_{SW}$ and Im(ε′/ε)=0) then applied *a posteriori* to find best values τ_s, Δm.

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

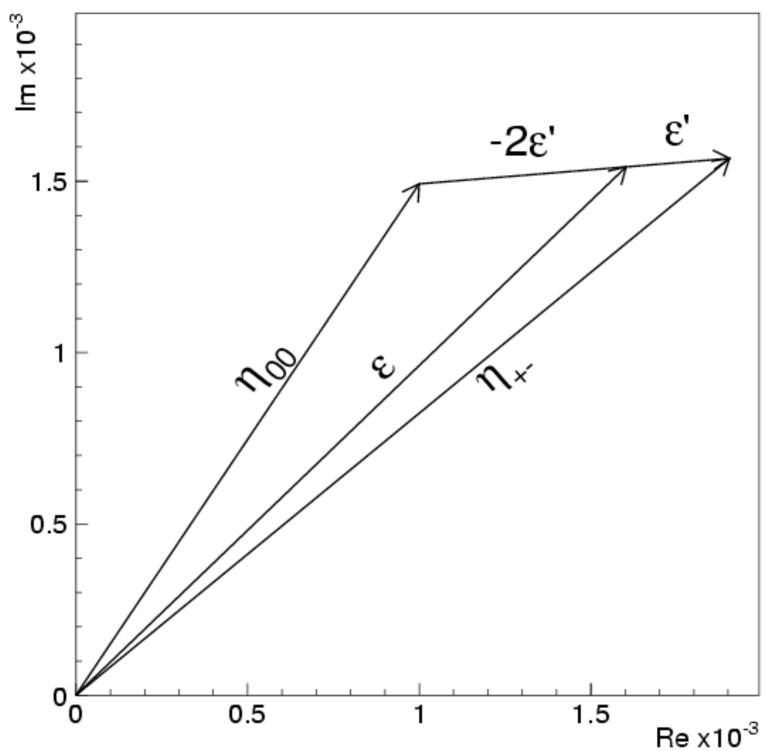
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right)$$

$$\phi_{+-} \approx \phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\phi_{00} \approx \phi_\varepsilon - 2\,\mathrm{Im}(\varepsilon'/\varepsilon)$$

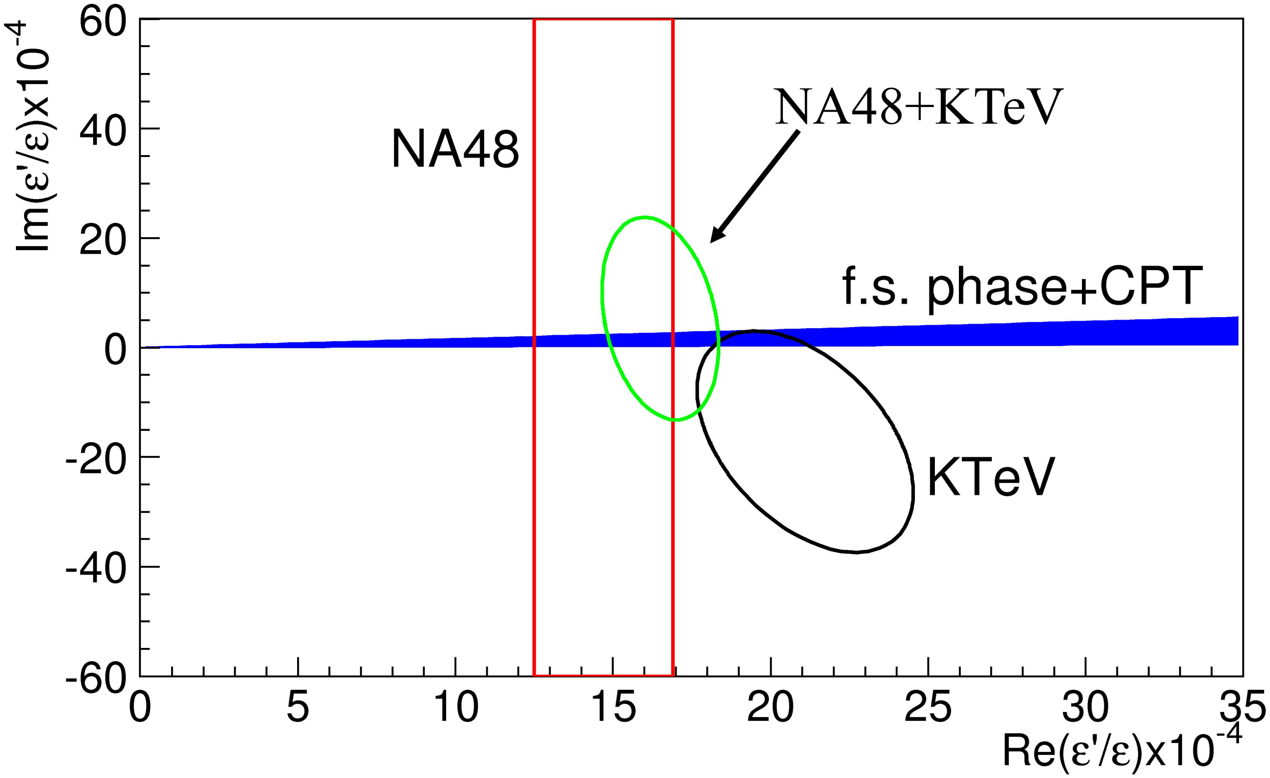
$$\Delta\phi \equiv \phi_{00} - \phi_{+-} \approx -3\,\mathrm{Im}(\varepsilon'/\varepsilon)$$



z-binned Fit Results

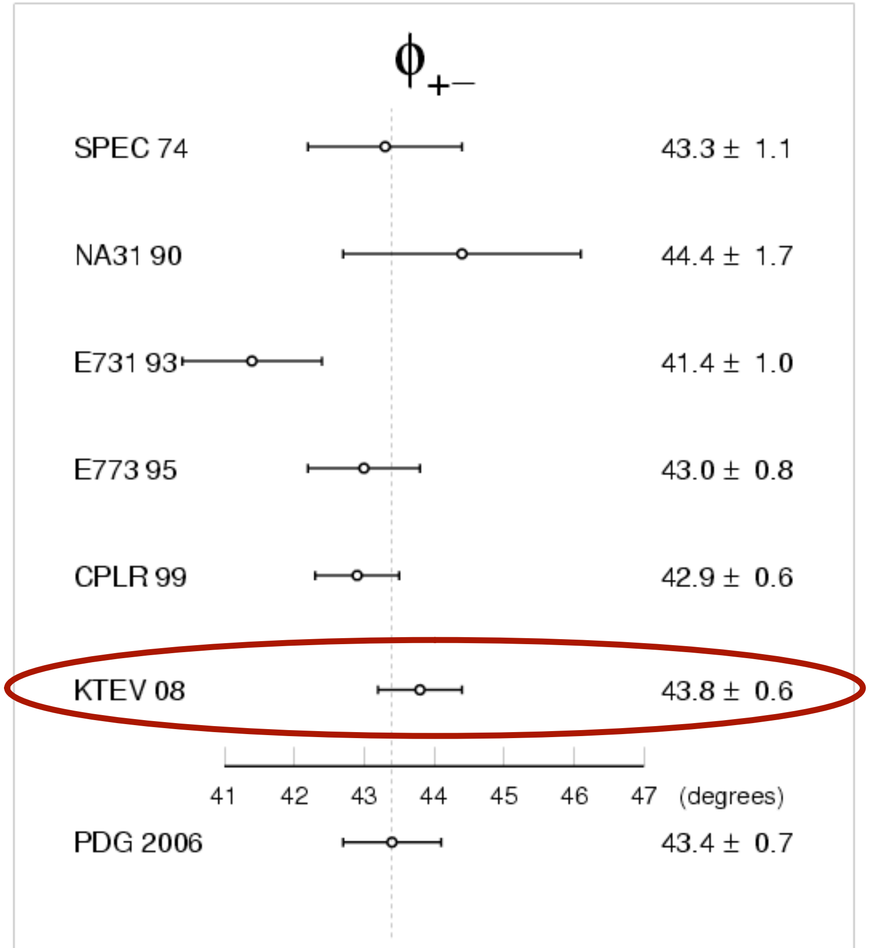
$$\phi_\varepsilon = (43.86 \pm 0.63)^\circ$$
$$\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)^\circ$$

$$\mathrm{Im}(\varepsilon'/\varepsilon) = (-17.2 \pm 20.2)\times 10^{-4} \Rightarrow \Delta\phi = (0.30 \pm 0.35)^\circ$$



All results consistent with CPT symmetry

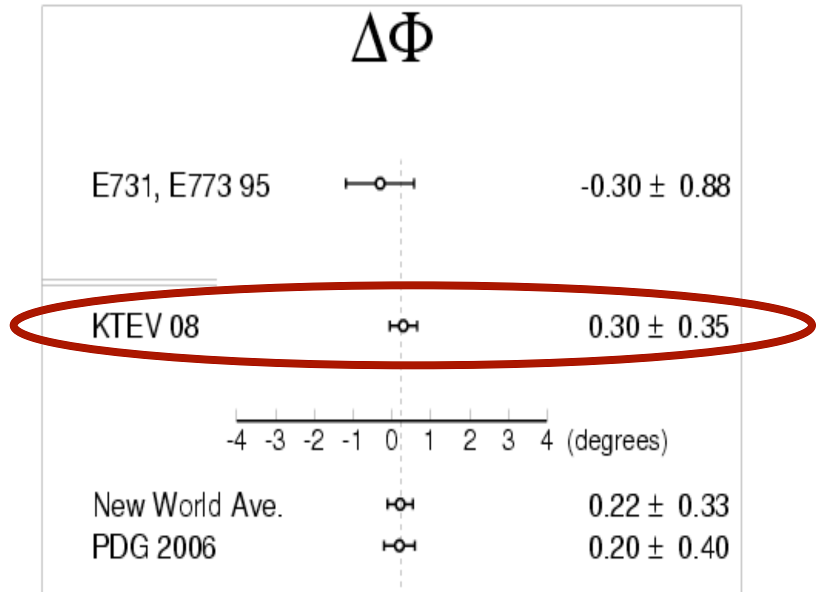
ϕ_{+-} and $\Delta\phi$



KTeV 2008: $\phi_{+-}=(43.8\pm 0.6)°$

(KTeV 2003: $\phi_{+-}=(44.1\pm 1.4)°$)

Improvement: better treatment of reg. transmission, screening

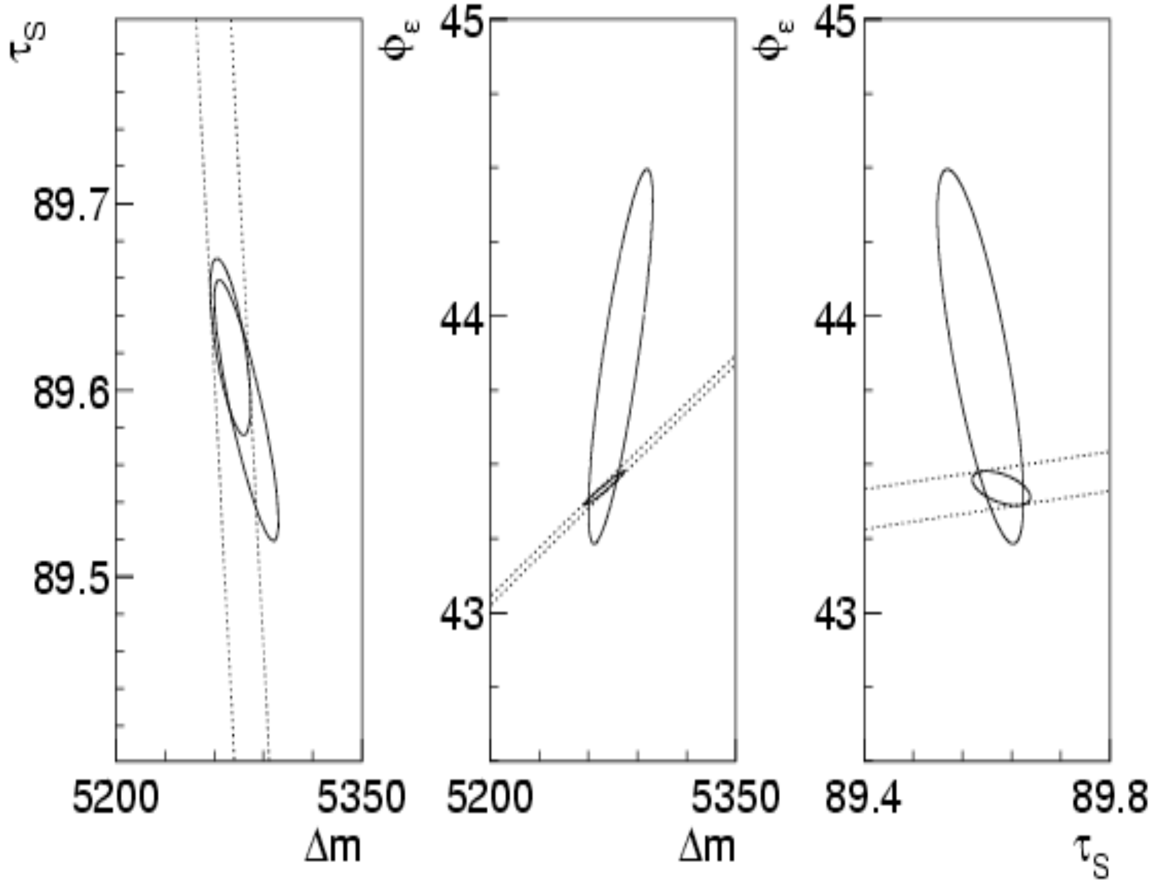


KTeV 2008: $\Delta\phi=(0.30\pm 0.35)°$

(KTeV 2003: $\Delta\phi=(0.39\pm 0.50)°$)

Improvement: neutral energy scale

z-binned Fit Results (cont)



No CPT constraint:

$\Delta m = (5279.7 \pm 19.5) \times 10^6\ \hbar s^{-1}$

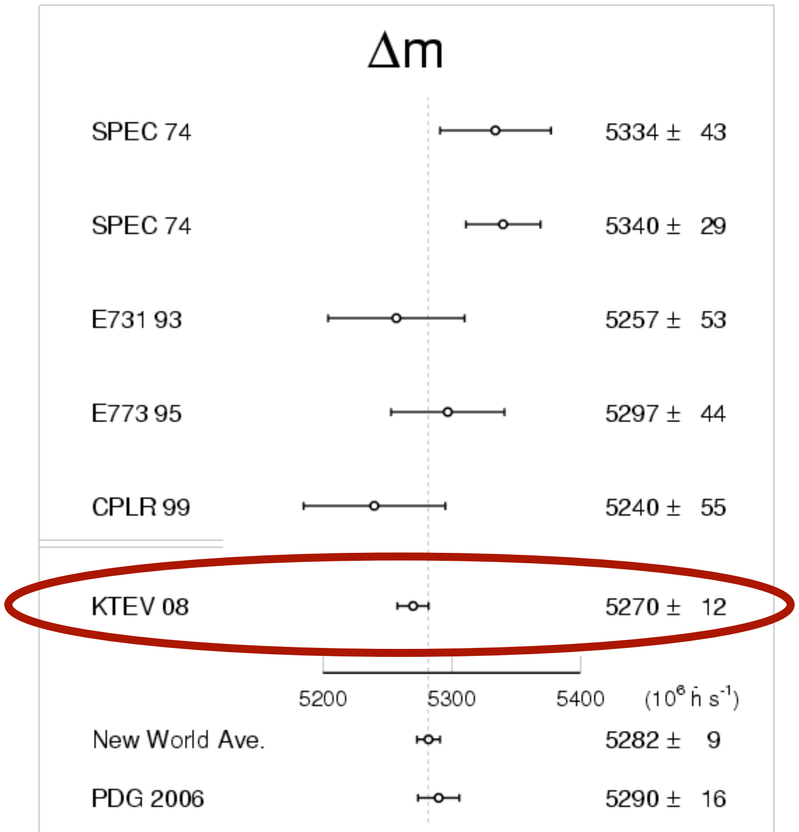
$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

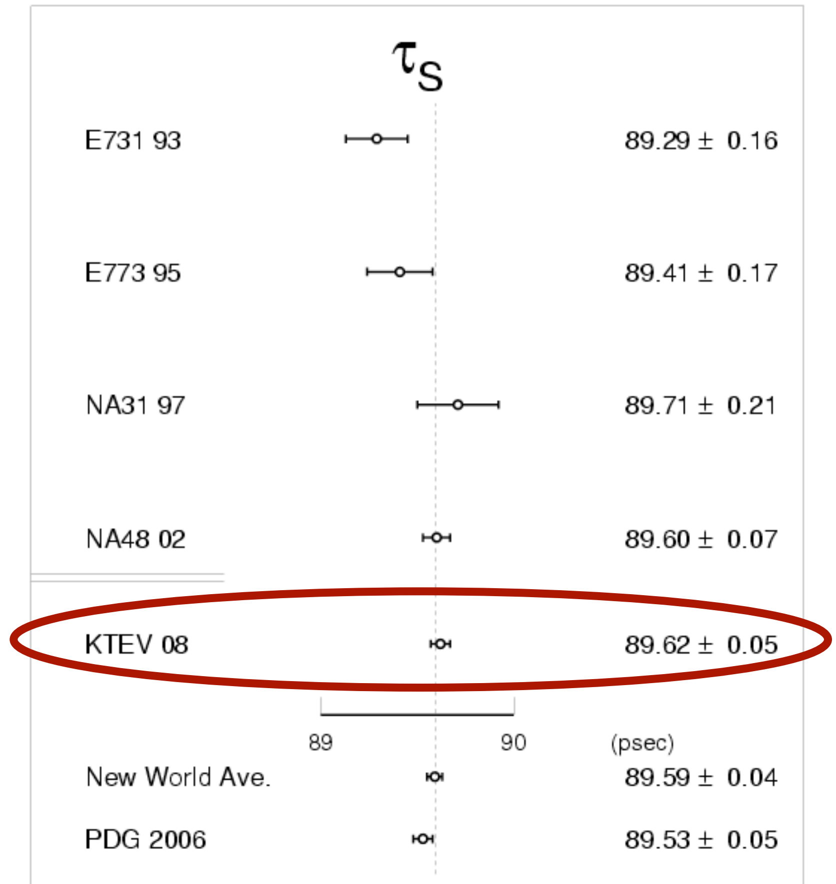
CPT constraint applied:

$\Delta m = (5269.9 \pm 12.3) \times 10^6\ \hbar s^{-1}$

$\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

Δm and τ_S





KTeV 2008: $\Delta m = (5270 \pm 12) \times 10^6\ \hbar s^{-1}$

(KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$)

KTeV 2008: $\tau_S = (89.62 \pm 0.05) \times 10^{-12}$ s

(KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12}$ s)

Summary

KTeV Results:

- $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
- $\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$
- $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

Assuming CPT

- $\phi_\varepsilon = (43.86 \pm 0.63)°$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
- $\Delta\phi = (0.30 \pm 0.35)°$

No CPT assumption

- Direct CP violation measured precisely:

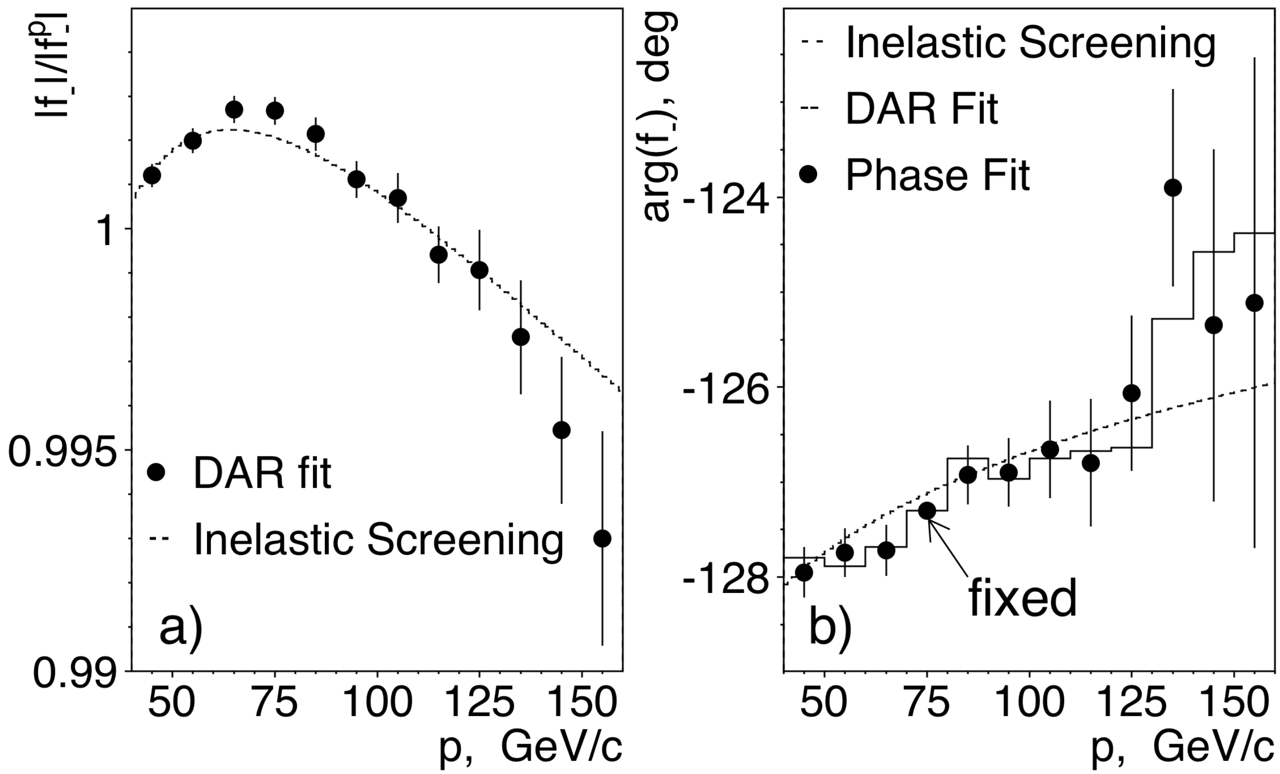
$$\frac{Rate(K^0 \to \pi^+\pi^-) - Rate(\overline{K}^0 \to \pi^+\pi^-)}{Rate(K^0 \to \pi^+\pi^-) + Rate(\overline{K}^0 \to \pi^+\pi^-)} = (5.5 \pm 0.5) \times 10^{-5}$$

- Future lattice calculations may make these precise experimental measurements equally precise tests of the Standard Model.

- All measurements are consistent with CPT symmetry.

EXTRA

Screening Corrections



•Determine regeneration amplitude in 10 GeV kaon momentum bins. Agrees with screening correction calculations for low P.

•Calculate phase at each P using Derivative Analyticity Relation using the 12 amplitudes

•Compare variation of the phase vs P from DAR to direct fit to data – good agreement.

$K_L \rightarrow \pi^0\pi^0$ Distributions